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TRAVELING DISTURBANCES IN THE IONOSPHERIC F-REGION AND THE SPORADIC E-REGION

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TRAVELING DISTURBANCES IN THE IONOSPHERIC F-REGION AND THE SPORADIC E-REGION * /1001**

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The results of an investigation of traveling disturbances (TD) over Tbilisi for the period 1964-1967 are reported. The relationship between TD and E_s is analyzed. It is shown that TDs can be associated with the propagation of internal gravity waves in the ionosphere.

So-called traveling disturbances (TD) are recorded among large-scale inhomogeneities. These disturbances travel in the horizontal direction at a velocity of 50-400 $m \cdot sec^{-1}$ over considerable distances without significantly changing their shape and amplitude [1-5]. Martyn [6] and Hines [7] have proposed to relate the appearance of such disturbances with the propagation of internal gravity waves in the ionosphere.

At the present time one of the probable reasons for the appearance of E_s at middle latitudes is assumed to be the so-called wind shear. This viewpoint, first advanced by Whitehead [8], has since been extensively developed and confirmed [9-12]. Hines [7, 9] found that wind shear can be associated with traveling disturbances. A correlation between E_s and these disturbances was noted in [13-17]. Therefore it is interesting to investigate further the relationship between TD and E_s to improve the theory of propagation of gravity waves and of the formation of wind shear in the ionosphere.

Different methods are used to investigate TD. The most popular method is to plot the height-frequency characteristics at ionospheric stations at small time intervals (1-5 minutes). Some results of an investigation of TD in the E_s-layer over Tbilisi, based on ionospheric data from January 1964 to December 1967, are reported below.

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*Report presented at the All-Union Ionospheric Conference, Leningrad, 1968.

**Numbers in the margin indicate foreign pagination.

The beginning of a TD is accompanied by loop-shaped distortions of ionograms in the vicinity of the critical F_2-layer frequencies (f_0F_2), in the form of a stratification, or in the low-frequency end of the F-region in the form of inflections. These distortions most often move toward the low-frequency end of ionograms and are called vertically traveling disturbances (VTD) [14-17]. VTDs are one of the most characteristic manifestations of traveling disturbances.

Figure 1 shows typical ionograms with moderately intense TDs. Two stratifications (at frequencies of 3.3 and 3.5 MHz) form at 12:10 p.m. at a height of about 200 km * and, almost simultaneously, an inflection starts to appear near 4.0 MHz (at a height of 240 km). A decrease in f_0F_2 is observed beginning at 12:15 p.m., which is accompanied by the movement toward lower frequencies of the "point" of separation of the O and X components. At 12:35 /1002
p.m. this point occurs at a frequency of 5.15 MHz. Beginning from 12:25 p.m. the inflection increases and moves downward. As it continues to move, the inflection changes into an E_s of the h type at 1:30 p.m.** This process lasts /1003
about 60 minutes. The formation and transformation of the inflection into an E_s is accompanied by a quasi-periodic f_0F_2 variation with a period of about 60 min. A decrease in electron density in the F-region can be observed during the formation of the E_s-layer of the h type (see Fig. 1 of [18]). This fact suggests that ionization can be transferred from the F-region into the E-region. Apparently, the movement of the "point" of separation of the O and X rays also indicates an actual displacement of dense ionized formations. TDs of this form are sometimes observed on ionograms also at night [19].

More intense TDs are mostly observed at comparatively low f_0F_2 ($4.5 \leq f_0F_2 \leq 6.5$ MHz). The ionograms in Fig. 2 show the successive passage of two intense TDs at an interval of 15 min. At 9:37 a.m. a VTD of the A1 type /1004
[14] begins to develop over the O component, reflected from the F-region at a height of about 530 km. Then a downward movement of the VTD and a strong change of the ionogram are observed. At 9:48 a.m. the ionogram shows traces of a reflection from the F_2- and F_1-layers at a minimum height of 325 and 200 km, respectively. A disturbance (VTD at height of 470 km) appears again at 9:52 a.m. As a result of these disturbances, F_0, $F_{0.5}$, and $F_{1.5}$ can be observed in the low-frequency end of the F-region (see the ionogram recorded at 10:09 a.m. and subsequent ionograms) and after their disappearance there is a marked increase in the critical frequency f_0E_s of the ordinary ray and of the blanketing frequency f_bE_s of the sporadic E-layer of the C type. It must be noted that an increase in f_bE_s and f_0E_s begins 11 min after the appearance of the TD in the F-region (see the ionogram recorded at 9:48 a.m. and subsequent ionograms).

*In the paper we use local time and virtual heights.

**A discontinuous trace of reflection at a height of 50 km is distinctly visible on the ionograms in Fig. 1. Similar reflections are fairly often observed at the Tbilisi ionospheric station. This phenomenon is of interest by itself and deserves attention; however, it is not our purpose to study the origin of the above reflections.

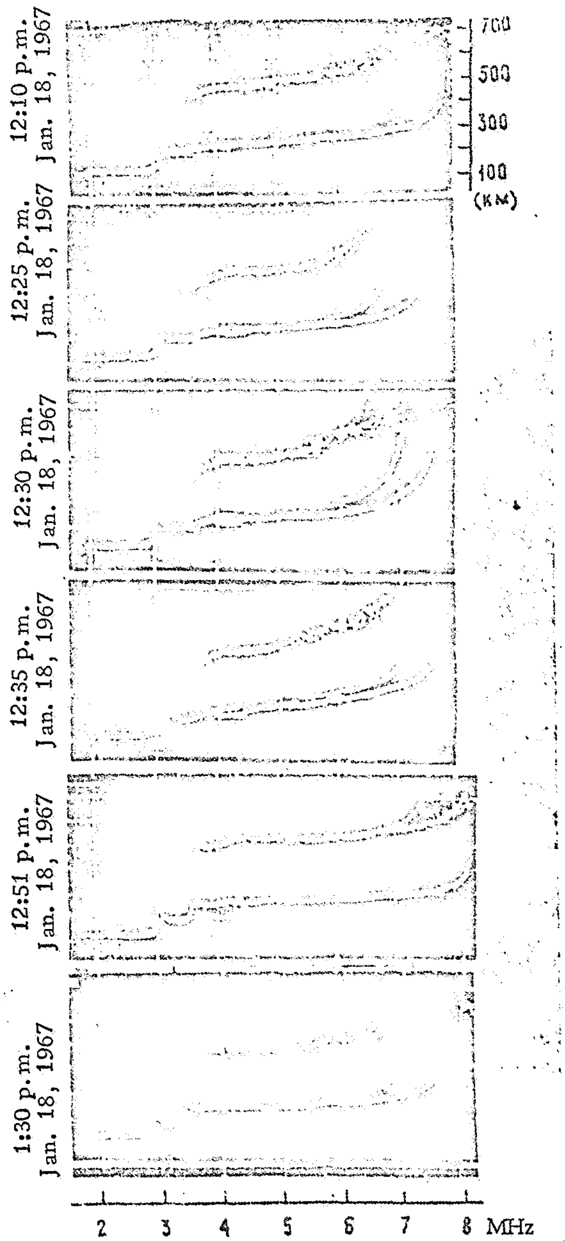

Figure 1. Height-Frequency Characteristics of the Ionosphere h'(f) in the Presence of TD (January 18, 1967).

It has been established from N(h)-profiles that the height at which the inflections at the low-frequency end of the F-region appear ranges from 160 to 200 km and that this height tends to increase with increasing solar activity. The vertical velocity of the downward motion of the inflections varies from 10 to 30 $m \cdot cm^{-1}$. The height at which a VTD appears in the

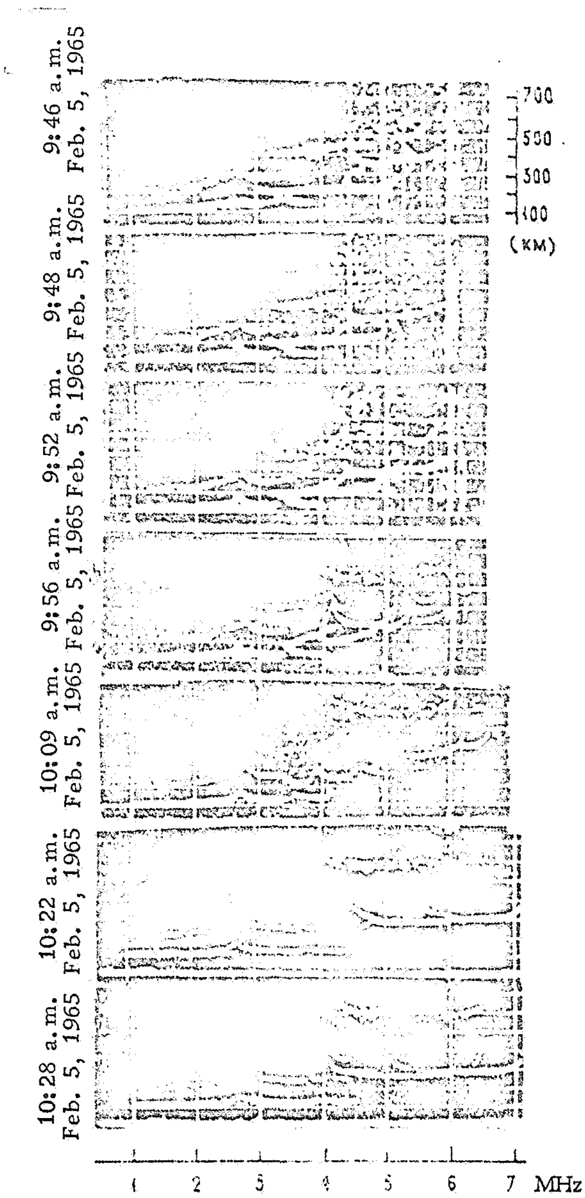

Figure 2. Complex Distortion of the Trace of the F-Region and an Increase in f_0E_s and f_bE_s in the Presence of Intense TD (February 5, 1965).

vicinity of f_0F_2 was determined approximately and lies in the interval 350-430 km. As f_0F_2 increases, the number of intense TDs at which VTD begin to appear above $N_{max}F_2$ decreases sharply and TD are virtually never observed for $f_0F_2 \geq 9.5$ MHz.

Investigation of ionospheric observations made at 1-min intervals also showed that intense TDs are sometimes accompanied by two or three sporadic layers which are located one above the other. Such an example is given in Fig. 3. At 10:00 a.m. an inflection appears in the trace of the F-region in the vicinity of 2.8 and 3.5 MHz at a height of about 200 km. From 10:07 a.m. f_0F_2 begins to decrease and instead of inflections in the low-frequency end of the F-region we can see more distinct stratifications that move downward. The "break" of these stratifications from the trace of the F-region becomes particularly noticeable starting from 10:15 a.m. and from this instant a disturbance can be observed in the vicinity of f_0F_2. Small stratifications appear first and then at 10:23 a.m. we can observe a VTD of the A1 type at a height of about 500 km. Stratifications which form at the low-frequency end of the F-region continue to move downward and at 10:34 a.m. they change into an E_s of the h type at a height of about 150 km. VTDs which form near f_0F_2 change at 10:32 a.m. into a downward moving inflection and at 10:47 a.m. we can observe two E_s-layers of the h and C types at heights of about 145 and 120 km, respectively. Two minutes later a third discontinuous and nonblanketing E_s-layer appears at a height of 100 km which persists for two minutes only.

It must be noted that at the instant this layer appears the trace weakens and the cutoff frequency of reflection of the type C sporadic E-layer decreases. After the discontinuous E_s-layer disappears, the F-region is restored to its former condition (see the ionograms recorded at 10:47 a.m., 10:49 a.m. and 10:52 a.m.). Subsequently two sporadic layers exist simultaneously for 30 min. A discontinuous E_s-layer is often observed at a height of 95-105 km also during the initial period of development of TD in the F-region. Such an example is shown in Fig. 4. The TD in the F-region was recorded at 11:14 a.m. (stratification in f_0F_2). At this time a regular E-layer and the ordinary component of a type C sporadic E are observed in the E-region at a height of 110 km. At 11:16 a.m. a discontinuous E_s-layer, which extends in frequency from 1.65 to 5.5 MHz, appears at a height of 100 km. At the same time a VTD appears in the vicinity of f_0F_2 at a height of about 500 km. Figure 4 shows that the variations in the intensity and cutoff frequency of reflection from the transparent E_s are quasi-periodic. /1005

We have calculated the N(h)-profiles for some short-lived E_s. It was found that a marked decrease in electron density occurs at a height of about 120 km 1-2 min before the appearance of such layers. We can therefore assume that the appearance and disappearance of discontinuous E_s-layers is accompanied by a change in electron density in the E-region. This is to be expected if we consider that the wind-shear mechanism of E_s formation implies a redistribution of ionization near the height at which the E_s-layer is recorded [8, 20]. From 1-min ionospheric observations it was found that a discontinuous, nonblanketing E_s-layer appears suddenly with a definite cutoff frequency. A layer of this kind persists from 1 to 18 min.

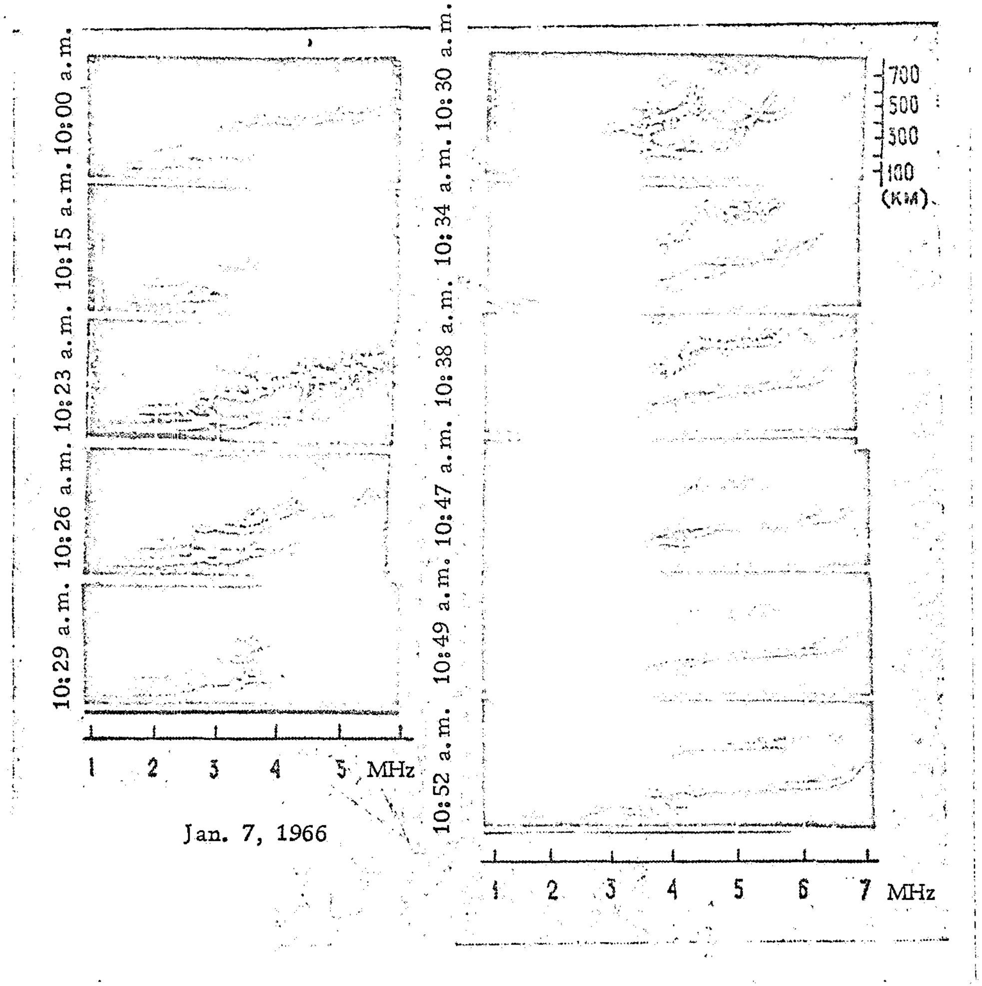

Figure 3. TD Accompanied by the Formation of Three Sporadic E-Layers (January 7, 1966).

Continuous ionospheric soundings during the winter of 1964-1965 show that the duration of two E_s-layers varies from 1 to 60 min. Most often these layers persist uninterruptedly for 5-20 min.

Although the foregoing picture is fairly typical for a TD, we must note that, in addition to the described anomalies, distortions of other types, associated with TD, are found on ionograms. For example, we can cite stratification, which is equivalent to the appearance of two reflections from the F-region. Anomalies of this type at night were described in [4, 21]. Figure 5 shows the development of this phenomenon during the daytime. It must be noted that only intense TDs are accompanied by this type of distortions. Two reflections from the F-region can be observed from 1:37 p.m. and they are particularly distinct at 1:39 p.m. Their virtual heights are about 300 and 225 km. The trace of the reflection from the greater height (in the range 4.2-6.9 MHz) moves upwards and becomes weaker. The duration of the two reflections from the F-region does not exceed 12-18 min. Figure 5 shows also /1006

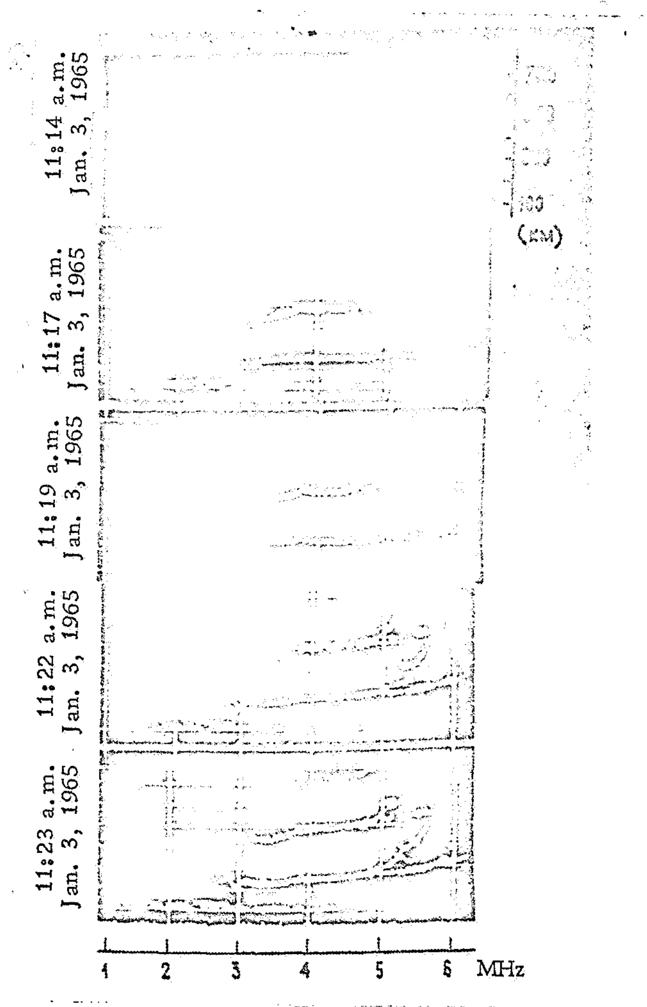

Figure 4. Short-Lived Discontinuous E_s in the Presence of a TD in the F-Region (January 3, 1965).

marked changes in the E-region. At the commencement of the disturbance there are two E_s-layers of the l and C types. The lower E_s-layer of the l type intensifies markedly for 11 min (see the ionogram recorded at 1:26 p.m.) and the E_s-layer of the C type can no longer be observed at 1:29 p.m. (ionogram not given). The cutoff frequency of the E_s-layer of the l type begins to decrease from 1:32 p.m. and from this instant the stratification starts to move downward (toward low frequencies) from a height of 215 km /1007 with a cutoff frequency of 3.2 MHz and, as a result, an E_s-layer of the h type forms at 1:48 p.m.

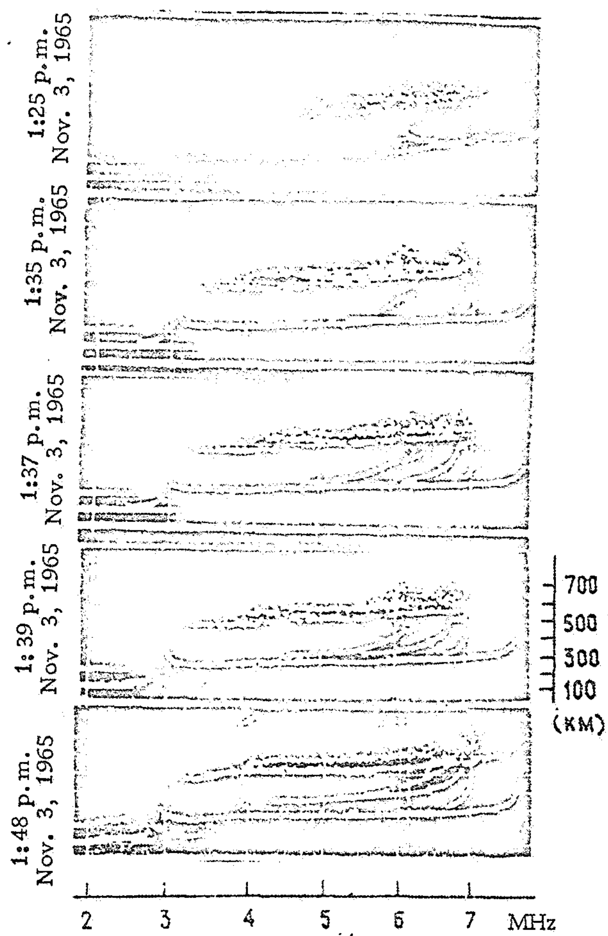

Figure 5. Appearance of Two Reflections from the F-Region caused by a TD (November 3, 1965).

It is evident from the figures that the penetration of a TD from the F- into the E-region is accompanied by the appearance of E_s. In the presence of such a layer the degree of ionization in it increases under the effect of the TD and this leads to an increase in the reflecting power of the E_s. In such cases the ionograms show the transformation of an inflection or stratification at the low-frequency end of the F-region into E_s. Intense variations of the E_s parameters can be observed 20-60 min after the appearance of a TD in the F-region. Such distinct transformations were not always observed on ionograms, but nevertheless TDs were accompanied by variations in f_0E_s and f_bE_s. In the above cases it was difficult to determine whether the variations in E_s parameters are associated with TD. Investigation of these variations, based on every-minute observations, showed that in the majority of cases they are quasi-periodic with a period of 10-60 min; this indicates that they are associated with TD [9].

The quasi-periodic variations in the f_0E_s and f_bE_s of E_s-layers of the h and C types are fairly often accompanied by marked variations in the height of the layer, $h'E_s$; sometimes these variations are also quasi-periodic. The /1008 height $h'E_s$ of an E_s-layer of the l type does not change significantly during the lifetime of the layer, irrespective of variations in f_0E_s and f_bE_s. Figure 6 shows the quasi-periodic variations in the parameters of E_s-layers of the l and h types, according to every-minute ionospheric observations. We can see that the $h'E_s$ fluctuations of an E_s-layer of the h type (the $h'E_s$ of an E_s-layer of the l type does not change) are out of phase with the f_0E_s and f_bE_s fluctuations. The maximum period of these fluctuations is 30-50 min and the minimum period about 8-10 min. The amplitude of the fluctuations ranges from 0.5 to 1.0 MHz for f_0E_s and f_bE_s, and for $h'E_s$ it is about 15 km. Similar variations of the E_s-layer parameters were noted in [22-24]. The quasi-periodic f_0E_s and f_bE_s variations are explained in [9] by the appearance of wind shear produced by gravity waves. This assumption is supported by the presence of two E_s-layers which are separated in height by 8-15 km. Furthermore, it was shown in [25] that the "effective wind shear" varies with a period from 10 min to 1 hour and more during the daytime.

A comparison of the variations in the E- and F-region parameters in the presence of TD shows once again that the disturbances are frontal [5, 18, 26]. The front of a TD is not always strictly linear. Sometimes it is a wavy line. The length of these vertical "waves" is about 70-100 km for fluctuations with a period of about 30 min. TDs with a forward sloping front are observed most frequently. The probability of appearance of an E_s-layer tends to increase when the front crosses the E-region. Yet, the critical E_s frequency increases sometimes, as pointed out by Bowman [27] for the nighttime. Sometimes, the quasi-periodic f_0E_s and f_bE_s fluctuations have the same shape for as long as 1-4 hours and are shifted in time by $\pm$ 5-25 min. This also indicates that TDs are frontal.

Figure 7 shows the quasi-periodic variations in the critical F-region frequency f_0F_2, the variations in virtual heights $h_f(t)$ at different fixed frequencies (in MHz as indicated on the curves), the variations in electron density $N_h(t)$ at different fixed heights (also indicated by numbers on the curves), and the variations in the critical frequency f_0E_s of an E_s of the h type. The triangles indicate the presence of discontinuous E_s-layers. The records clearly show the

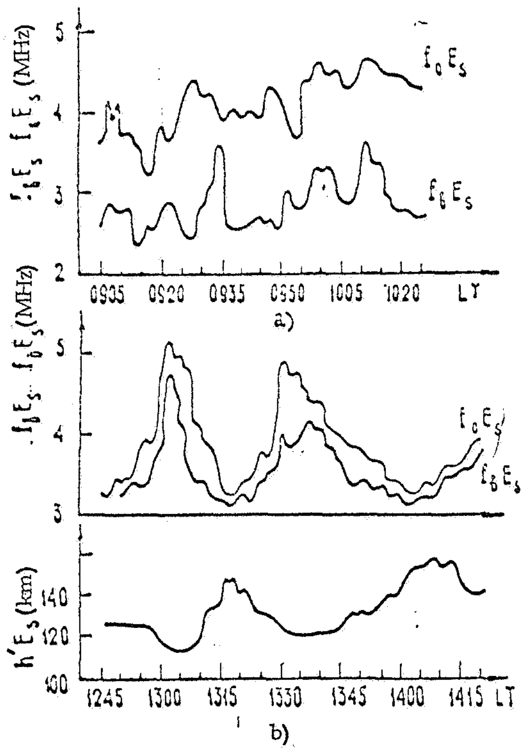

Figure 6. Quasi-Periodic Variations of the Parameters of a Sporadic E-Layer of the *l* Type (a), January 26, 1966, and of the h Type (b), September 29, 1969.

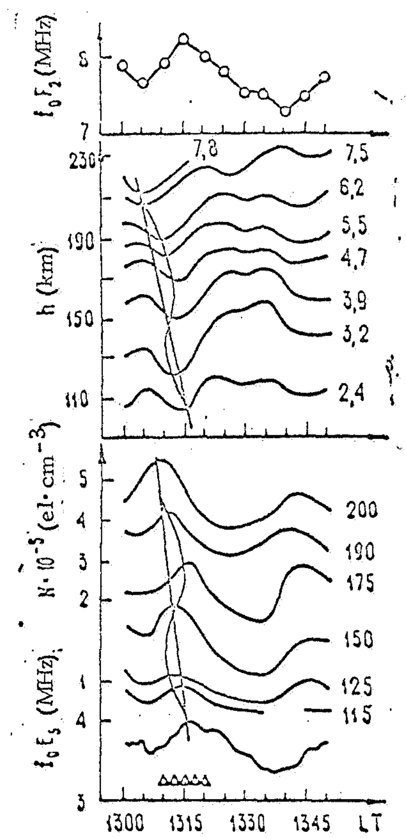

Figure 7. Characteristic Pattern of Variation of Different Parameters (f_0F_2, $h_f(t)$, $N_h(t)$, f_0E_s) of the Ionosphere in the Presence of a TD (December 12, 1966).

foregoing characteristics. Hines has shown [28] that the bending of the wave front of a TD is caused by the dissipation and refraction of gravity waves which propagate in a medium with a varying temperature and a prevailing wind.

Continuous ionospheric soundings have made it possible to investigate also the instants at which f_0E_s and f_bE_s begin to vary in the presence of a TD in the F-region. We have analyzed 517 TDs in all. It was found that the maximum number of variations in an E_s-layer is observed 10-15 min and 30-60 min after the appearance of a TD in the F-region. We have observed variations in an E_s at the instant of or 5-15 min after the appearance of a TD in the F-region. It must be noted that an increase in f_0E_s and f_bE_s at the instant of development of a TD in the F-region is more typical for an E_s-layer of the

l type at a height of 100-110 km. Variations in f_0E_s and f_bE_s which occur close ($\pm$ 5-15 minutes) to the beginning of a TD in the F-region can apparently be explained by the frontal nature of TD. It was also established that the probability that a TD will affect an E_s increases with decreasing f_0F_2 and for $4.6 \leq f_0F_2 \geq 5.3$ MHz it reaches 65%.

Using the results of ionospheric observations on an accelerated schedule, we have investigated the periods of quasi-sinusoidal disturbances in the E- and F-regions by parameters, f_b, E_s, f_0E_s, f_0F_2, $N_h(t)$, $h'_f(t)$, $h_f(t)$. We found that /1009 the periods of the disturbances change within an interval of 10 to 180 min. Disturbances with a period of 30 and 60 min are most often observed. It was found that the number of disturbances with a period of $n \times 30$ min ($n = 1, 2, 3, 4, 5, 6$) tended to increase. The minimum period of quasi-sinusoidal f_0E_s and f_bE_s variations is at least 8-10 min and for the F-region parameters $T_{min} \geq 15$ minutes. These values undoubtedly favor the assumption that TDs are associated with internal gravity waves. When solar activity increases, the number of quasi-periodic disturbances in the F-region decreases and fluctuations with periods greater than 90-120 min are not observed. Even the amplitude of the disturbances decreases markedly. The fluctuations of ionospheric parameters are not monochromatic as a rule. In the F-region this is particularly noticeable when the f_0F_2 values are low. It is therefore more correct to associate a TD with groups of waves [12] rather than with separate monochromatic waves.

The relative deviations of electron density $\Delta N/N$ vary from 3 to 7% for weak disturbances and reach 15-20% for strong TDs. There are cases when $\Delta N/N$ is about 35-50%. It must be noted that the amplitude of a disturbance tends to increase with decreasing density in the F-region itself.

From the foregoing we can draw the following conclusions. /1010

1) TDs can be associated with the propagation of internal gravity waves in the ionosphere. The main features of TDs can be explained within the framework of this mechanism.

2) A VTD is one of the typical manifestations of TDs. However, the explanation of VTD as the apparent vertical displacement of disturbances produced by the slope of the TD front needs to be refined since in this case a real transfer of ionization is frequently observed near f_0F_2 and in the inter-layer E-F region. Since VTDs at heights of 350-430 km are mainly observed when the f_0F_2 values are low, it can be assumed that when electron density in the F-region is low, the TD effect extends even above $N_{max}F_2$ (that a TD can penetrate to 500 km was pointed out in [29]).

3) The inverse relationship between the number of intense TDs and solar activity (f_0F_2) can be explained by an increase in the absorption of gravity waves in the ionosphere with increasing electron density.

4) The inter-layer stratifications E_2, F_0, $F_{0.5}$, $F_{1.5}$ are often caused by TDs.

5) TDs cause marked variations in the parameters of the sporadic E-layer.

6) The quasi-periodic variations in f_0E_s and f_bE_s with a period of 10-60 min speak in favor of Hines' assumption that wind shear may be associated with internal gravity waves.

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